GEOLOGICAL CONSTRAINTS ON TIDAL AND ROTATIONAL DEFORMATION ON EUROPA.

P. H. Figueredo, Department Geological Sciences, Arizona State University, Tempe, AZ 85287-1404, figueredo@asu.edu.

1. Introduction: Orbital resonances with Io and Ganymede maintain a permanent eccentricity in Europa's orbit around Jupiter [1]. This situation produces a) 'diurnal' variations in the tidal figure of Europa during its 85 hr orbit, leading to dissipative heating as well as surface stresses, and b) a non-zero average tidal torque, which can drive nonsynchronous rotation (NSR) of the satellite [2, 3]. In addition, any mass concentration away from the equator could trigger episodes of polar wander of the outer cryosphere, if detached from the interior by a liquid layer [4]. Over the past few years, researchers have modeled the stress fields associated with these processes and their variation with space and time, from which they predicted specific orientations and trends in the lineament record of Europa [e.g., 3, 5-7]. In this review, I summarize the geological evidence for tidal and rotational processes on Europa as reflected in Voyager and (especially) Galileo images of the satellite. I address the constraints they place in the conditions and rates of deformation, the ongoing discrepancies in the interpretation of the data and their implications, and some ways of resolving outstanding issues.

2. Nonsynchronous rotation (NSR): The average gravitational torque of Jupiter on Europa's misaligned tidal figure tends to make Europa's rotation rate faster than synchronous [2], even in a completely solid body. An internal ocean would allow the decoupled outer shell to rotate nonsynchronously, drifting eastward over the tidally deformed interior. NSR stresses in the cryosphere are cumulative (until relieved by failure) and can match the magnitude of diurnal stresses with just ~1° of rotation [e.g., 3]. Therefore NSR likely constitutes the main source of stress for tectonic activity on Europa.

2.1. Fracturing: Fracturing of the cryosphere by tidal stresses (<0.4 kPa) requires the ice to be thin and weak. Widespread fracturing of Europa is in itself evidence of either an extremely thin shell, inconsistent with most thickness estimates (e.g., [8]), or an extra source of stress in the cryosphere. The pattern of global fractures on Europa and its offset with respect to the tidal stress pattern is consistent with NSR stresses [3, 5-7]. Stress models achieve better matches with the lineament record when both sources of stress, tidal and NSR, are combined [e.g., 3]. As discussed in section 3.1, the propagation of cycloidal fractures was likely controlled by diurnal stresses [9]; features that are not cycloidal possibly resulted from rapid propagation or were driven by NSR stresses.

2.2. Translation of features: As the outer ice shell moves eastward, surface features are expected to migrate from their original longitude of formation. The major lineaments on Europa can be explained as tensile cracks within a stress field with diurnal and NSR components only after translating these features westward a few tens of degrees or more [e.g., 6, 7, 10, 11]. In the same way, the orientation and sense of shear of strike-slip features in some areas fit better global stress models if they formed west of their current locations [3, 10]. It is generally considered that during the eastward migration of the cryosphere, fractures progressively relieve the accumulated NSR stress; this scenario could be confirmed when a global stratigraphic framework is established. The number of fractures formed during each rotation could constrain the number of rotations recorded in the visible geologic record (i.e., the last 30-80 Myr [12]) from which we can put an upper limit to the rate of NSR. On this basis, the NSR rate was estimated as <240,000 yr [10] from displacements of cycloids in one locality (and >12,000 yr from the lack of displacements of features between Voyager and Galileo images [13]), assuming a constant rate of 1-2 fractures per cycle. However, indications of repeated fracturing per cycle [11, 14-16, section 2.3] and of a rapid drop in the rate of tectonic resurfacing during the visible geologic record [17, cf. 18] challenge these assumptions.

As the outer shell of Europa moved eastward with respect to the deformed interior, it would become stretched where it moves over the tidal bulges, and compressed as it moves away from them [3]. Thus an area around the equator should have experienced cycles of extension and compression. The geologic record shows no widespread evidence of such alternation of stress conditions, although structural trends suggestive of shear failure at low latitudes have been reported [19]. In this sense, the evidence for compressional low-albedo bands, ridges, or folds [20-23] remains limited, and their relationship to tidal and rotational processes has not been addressed in detail. If the NSR rate was relatively fast, as implied by some studies [10], one would expect longitudinal 'smearing' of units formed under specific stress conditions (notably at low latitudes), with activity migrating westward with time. Despite the current lack of uniform coverage and a global stratigraphic network on Europa, there seems to be no obvious indication of such a progression or of smearing [24]. While the few impact craters on Europa show no leading/trailing asymmetries in their distribution [12], supporting rapid NSR, the distribution of other units appears to vary strongly with longitude. Chaos regions roughly match the location of the equatorial zones of NSR isotropic compression [25] and maximum tidal dissipation [11, 26, cf. 27]; the extensional wedges of Argadnel Regio are located roughly over one equatorial zone of isotropic extension [28], without an antipodal counterpart. If these units originated from global stresses, then the late NSR rate seems to have been very slow; alternatively, the units could have resulted from endogenic activity, with possible influence from tidal processes [29, 30].

2.3. Lineament rotation: One of the NSR model predictions is the systematic rotation of lineaments with time, if they originated as tensile fractures [8, 28]. Consistent with this prediction, and strengthening the case for both NSR and tensile fracturing of the cryosphere, several researchers have reported progressive clockwise and counterclockwise lineament rotations in the northern and southern hemispheres, respectively [e.g., 11, 15, 16, 28, 31]. The amount of rotation recorded by the most prominent lineaments varies considerably, from 25° to more than 700°. These results and their interpretation are complicated by the possibility of shear failure in some areas [19], the formation of only a few fractures per cycle [10], ambiguities in the sense of rotation [32], and the possibility of polar wander [4, 20]. Definitive evidence for the rotation of lineaments with time should come from detailed (i.e., lineament-by-lineament) stratigraphic studies in more locations and the development of a global stratigraphic framework for Europa.

3. Diurnal tides: The periodic reorientation of the tidal figure of Europa during each orbit causes oscillations in the global diurnal stress field. During each cycle, stresses in a given region change from tensile to compressional as they rotate and change amplitude [3]. The magnitude of the tidal stresses, which depends on the thickness of the cryosphere, is estimated to be <40 kPa. The effects of diurnal tides seem reflected in several tectonic features on Europa:

3.1. Cycloidal fractures: The origin of Europa's conspicuous chains of curved segments, or cycloids, has been successfully explained by Hoppa et al. [9] in the framework of diurnal tidal stresses. During an orbit and under sufficient tensile stress, a fracture will propagate in a curved path in response to the rotation of the local stress field, producing an arc segment. Subsequent orbits will add continuous arc segments as long as the crack remains active. The length of each arc, their radius and sense of curvature, and the 'pointiness' of the cusps between arcs can be reproduced by varying the ice strength and the speed and direction of fracture propagation. Tidal stresses predict the formation of concentric sets of tight, 'boxy' arcs around the sub- and antijovian points of Europa, with more linear cycloids extending between them [9, 14]. Such a pattern seems consistent with the formation of Argadnel Regio (the "wedges" region) in the past, although no equivalent is found at the antipode.

3.2. Strike-slip features: Models of fault 'walking' by diurnal tidal stresses predict sinistral and dextral strike-slip displacements to dominate in the northern and southern hemispheres, respectively; at latitudes £30°, the sense of displacement is also a function of the fault azimuth and longitude of formation [20, 33]. Overall, these trends are consistent with the geologic record of strike-slip features [11, 20, 33]. Some inconsistencies exist, although they are generally attributed to the effects of NSR [33] and polar wander [20]. Details on the mechanism, however, await more thorough studies on issues such as a) the reasons why not all fractures underwent walking, even in polar regions; b) the along-strike variations in offset; c) the effectiveness of walking for very long faults; and d) the relationship between the amount of offset and the structure accommodating it. In this sense, the existence of simple fractures associated with significant lateral offset [15] is inconsistent with most ridge-building mechanisms, as discussed in section 3.3. Strike-slip is assumed in most analyses to result from primary tidal walking, although many of them could be secondary features accommodating deformation elsewhere. Structural studies are needed to identify morphological distinctions between the two processes, which could provide alternative explanations for some of the mentioned uncertainties.

3.3. Ridge-building: While tidal stresses most likely are combined with NSR stresses to fracture the brittle cryosphere (section 2.1), diurnal processes can operate in the enlargement of a crack into ridges or more developed morphologies [3]. According to some models, tidal working of fractures builds ridges by diurnal 'pumping' of crushed ice and slush from an ocean [3] and/or shear at more shallow levels [34]. It is argued that tidal pumping and strike-slip motions require fractures to extend through a relatively thin cryosphere [3, 10], despite issues with overburden pressure and ductile ice. This is not necessarily the case; for example, melts generated by shear could be pumped through fractures. Only dilational bands seem to involve a more intimate connection with the ocean as well as other sources of stress like secular variations, NSR, ocean currents, or convection cells [e.g., 29, 35-37]. Alternative 3-D structures of faults and geomorphological studies assessing systematically the intersections between ridges, variations at cycloid cusps and areas of sharp change in fault azimuth are necessary to refine models of ridge-building by diurnal tides.

4. Polar wander: Polar wander of a detached outer cryosphere was proposed as a possible consequence of the centrifugal displacement towards the equator of any mass concentration originally at higher latitudes [4]. Polar wander has been invoked to explain essentially any departure in the distribution of features (e.g., lineaments, chaos, wedges, and strike-slip features [7, 15, 20, 28]) from the equatorial symmetry of the tidal and NSR models. Interpretation of the evidence becomes uncertain, as the reported amounts of displacement and possible pivoting points differ considerably, which could be an expected effect of polar wander events in a nonsynchronously rotating Europa. It is worth noting, however, that if polar wander occurred relatively late (as suggested by [20]), it would render invalid most of the detailed correlations between lineaments and global stress fields [e.g., 3, 9-11, 16] that are considered in support of the tidal and NSR models.

5. Conclusions and outstanding issues: The geologic record indicates that tidal and rotational deformations are likely the main driver for geologic activity on Europa. To assume the initiation of lineaments as tensile cracks provides good matches with tidal and rotational stress patterns; the possibility of failure by shear and especially bending stresses should be considered for certain locations and times. Diurnal tidal stresses successfully explain the origin and characteristics of Europan cycloids, strike-slip displacements, and possibly ridges, but they involve fractures to form under very weak tensile stresses and to propagate through the entire cryosphere. In this sense, alternative fault geometries, dislocation scenarios, and sources of melt should be explored in order to determine if these conditions are indeed a requirement. NSR can accumulate adequate amounts of stress for failure and tends to match the overall pattern and sequence of lineaments on Europa. Fundamental constraints on this process, like the amount and rate of rotation, should become clearer from future results from lineament-by-lineament stratigraphy, terminator observations, and geophysical measurements. The evidence for polar wander, especially on recent times, should be considered with caution until supported in combination with global stress models or observations of actual displacement.

References: **[1]** Peale et al. 1979, *Science* 203: 892; **[2]** Greenberg and Weidenschilling 1984, *Icarus* 58: 186; **[3]** Greenberg et al. 1998, *Icarus* 135: 64; **[4]** Ojankangas and Stevenson 1989a, *Icarus* 81: 220; **[5]** Helfenstein and Parmetier 1985, *Icarus* 61: 175; **[6]** McEwen 1986, *Nature* 321: 49; **[7]** Leith and McKinnon 1996, *Icarus* 120: 387; **[8]** Pappalardo et al. 1999, JGR 104: 24015; **[9]** Hoppa et al. 1999a, *Science* 285: 1899; **[10]** Hoppa et al. 2001, *Icarus* 153: 208; **[11]** Figueredo and Greeley 2000, *JGR* 105: 22629 ; **[12]** Zahnle et al. 2003, *Icarus* 163: 263; **[13]** Hoppa et al. 1999b, *Icarus* 137: 341; **[14]** Bart el al. 2003, *LPSC* 34: #1396; **[15]** Figueredo and Greeley 2003, *LPSC* 34: #1017; **[16]** Kattenhorn 2002, *Icarus* 159: 490; **[17]** Figueredo and Greeley, *Icarus*, in press; **[18]** Basilevsky and Head 2002, *Geology* 30: 1015; **[19]** Spaun et al. 2003, *JGR* 108: JE001499; **[20]** Sarid et al. 2002, *Icarus* 158: 24; **[21]** Greenberg et al. 2003, *LPSC* 34: #1861; **[22]** Patterson and Pappalardo 2002, *LPSC* 33: #1681; **[23]** Prockter and Pappalardo 2001, *Science* 289: 941; **[24]** Figueredo 2002, *PhD dissert.*, ; **[25]** Pappalardo et al. 1998, *LPSC* 29: #1732; **[26]** Riley et al. 2000, *JGR* 105: 22599; **[27]** Ojakangas and Stevenson 1989b, Icarus 81: 242; **[28]** Geissler et al. 1998, *Nature* 391: 368; **[29]** Pappalardo and Head 2001, *LPSC* 32: #1866; **[30]** McKinnon 1999, *GRL* 26: 951; **[31]** Geissler et al. 1999, *LPSC* 30: #1743; **[32]** Sarid et al.. 2003, *LPSC* 34: #1445; **[33]** Hoppa et al. 1999c, *Icarus* 141: 287; **[34]** Nimmo and Gaidos 2002, *JGR* 107: JE001476; **[35]** Tufts et al. 2000, *Icarus* 146: 75; **[36]** Greenberg et al. 2002, *Rev. Geophys* 40: RG000096; **[37]** Prockter et al. 2002, *JGR* 107: JE001458.